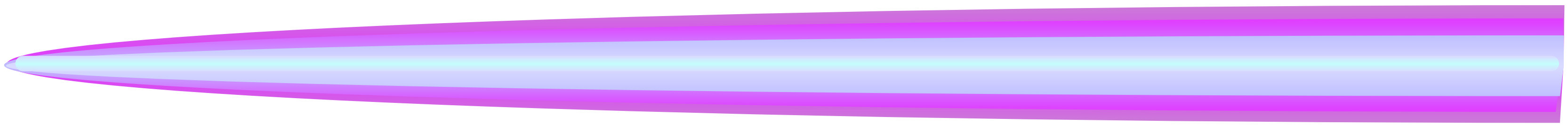


The Challenge of Ambient Plasma Wave Propulsion

19th Advanced Space Propulsion Workshop

Jim Gilland, George Williams

Ohio Aerospace Institute

This work was performed under funding from the NASA Innovative and Advanced Concepts Program

Leveraging Resources through Collaboration

Outline

I. Justification

II. Concept Description

III. Approach

IV. Results

- A. Magnetosphere Modeling
- B. Wave Propagation
  - Ray tracing
- C. Antenna System
  - Sizing and power loading

V. Conclusions

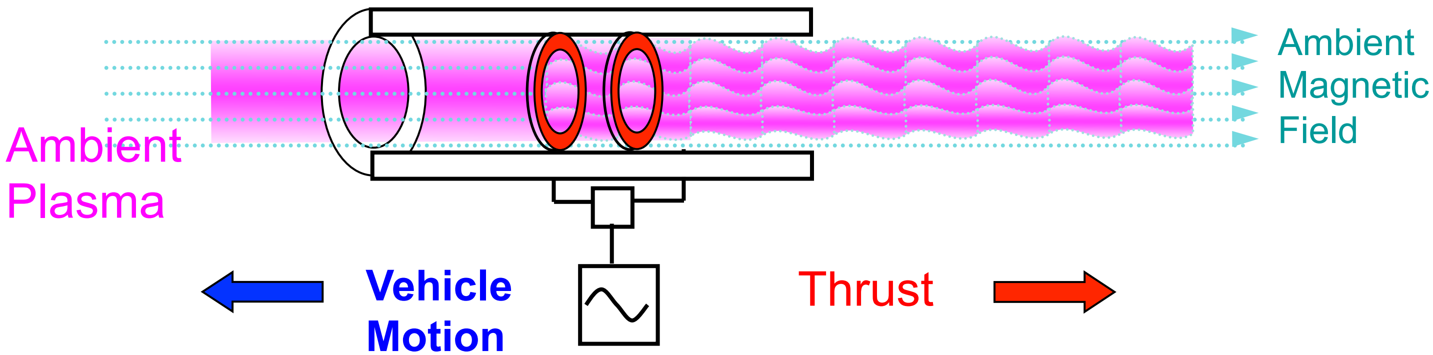
VI. Future Work

Justification

- Robust space exploration will ultimately require “living off the land”
- In-Situ propellants and propulsion will reduce launch needs
  – “Near Term” advanced propulsion (chemical, nuclear thermal, NEP) require IMLEO ~ 300 – 1000 mT
  – Feasibility of launching such masses on a regular basis is small
- Need to examine potential extraterrestrial sources for propulsion

OAI
Leveraging Resources through Collaboration

Concept Description



- Utilize onboard power to couple to environment through plasma waves
  - First look: Alfven waves
    - Observed naturally in astrophysics
    - Postulated as mechanisms for heating and particle acceleration
- Radiate wave energy directionally to produce motion
  - Antennae designed to couple to correct wave and direction
  - Thrust ~ Wave field energy $\frac{\partial B^2}{2\mu_0}$

Leveraging Resources through Collaboration

APPROACH

Leveraging Resources through Collaboration

Analysis Approach

- Develop physical models for wave production/ propulsion
- Assess possible environments
- Model wave propagation in relevant environments (Ray tracing)
- Use propagation results in system design (ANTENA rf plasma code)
  - Antenna size
  - Antenna loading (power)
  - Thrust

Alfven Wave Physics

- Low frequency waves in magnetized plasmas
- 3 modes:
  - Shear (|| B) $\omega = k\cos(\theta)V_A$
  - Compressional (isotropic) $\omega = k\,V_A$
  - Magnetoacoustic ($\perp$ B) $\omega^2 = k^2(v_A^2 + c_s^2)$

$$V_A = \sqrt{\frac{B_0^2}{\rho\,\mu_0}}$$

$$c_s = \sqrt{\frac{T_e}{M_i}}$$

- Observed in terrestrial, Jovian, and Solar magnetospheres
  - Offered as possible explanation for coronal heating, acceleration of solar wind, Io plasma torus interactions

OAI
Leveraging Resources through Collaboration

Ray Tracing Approach

- Dispersion relation gives wavelength and frequency as functions of environment (B, ρ)

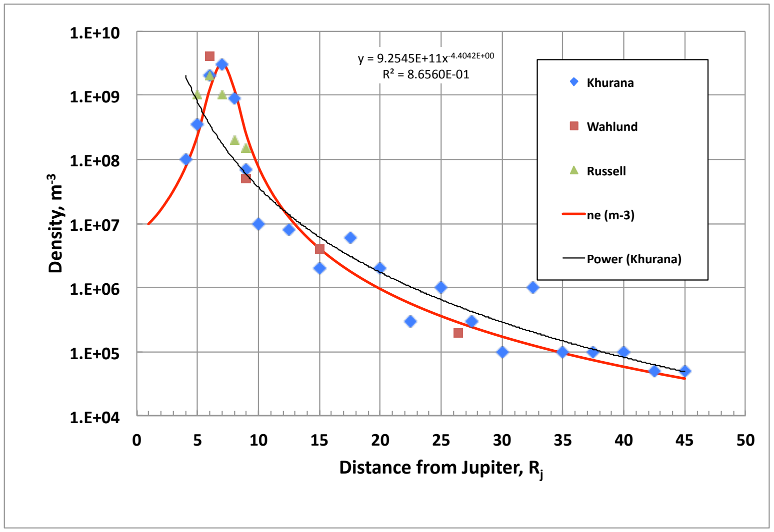
$$(\omega^2 - k_z^2 V_A^2)(\omega^4 - \omega^2 k^2 (V_A^2 + c_s^2) + c_s^2 V_A^2 k^2 k_z^2) = 0$$

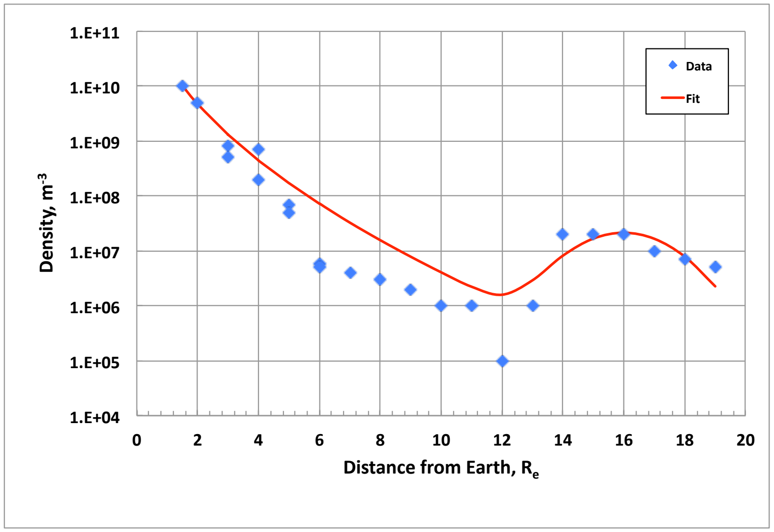
$$\vec{V}_A(x.y,z) = \frac{\vec{B}(x.y,z)}{\mu_0 \rho(x,y,z)} \qquad c_s = \sqrt{\frac{kT_e}{M_i}} \qquad k = \sqrt{k_z^2 + k_\perp^2}$$

- Wavelength (k) depends on position through magnet and density fields
- Ray tracing follows wave energy as it propagates in magnetosphere
- Requires representative initial conditions
  - (x,y,z), (k_x, k_y, k_z)

OAI
Leveraging Resources through Collaboration

Magnetosphere Models

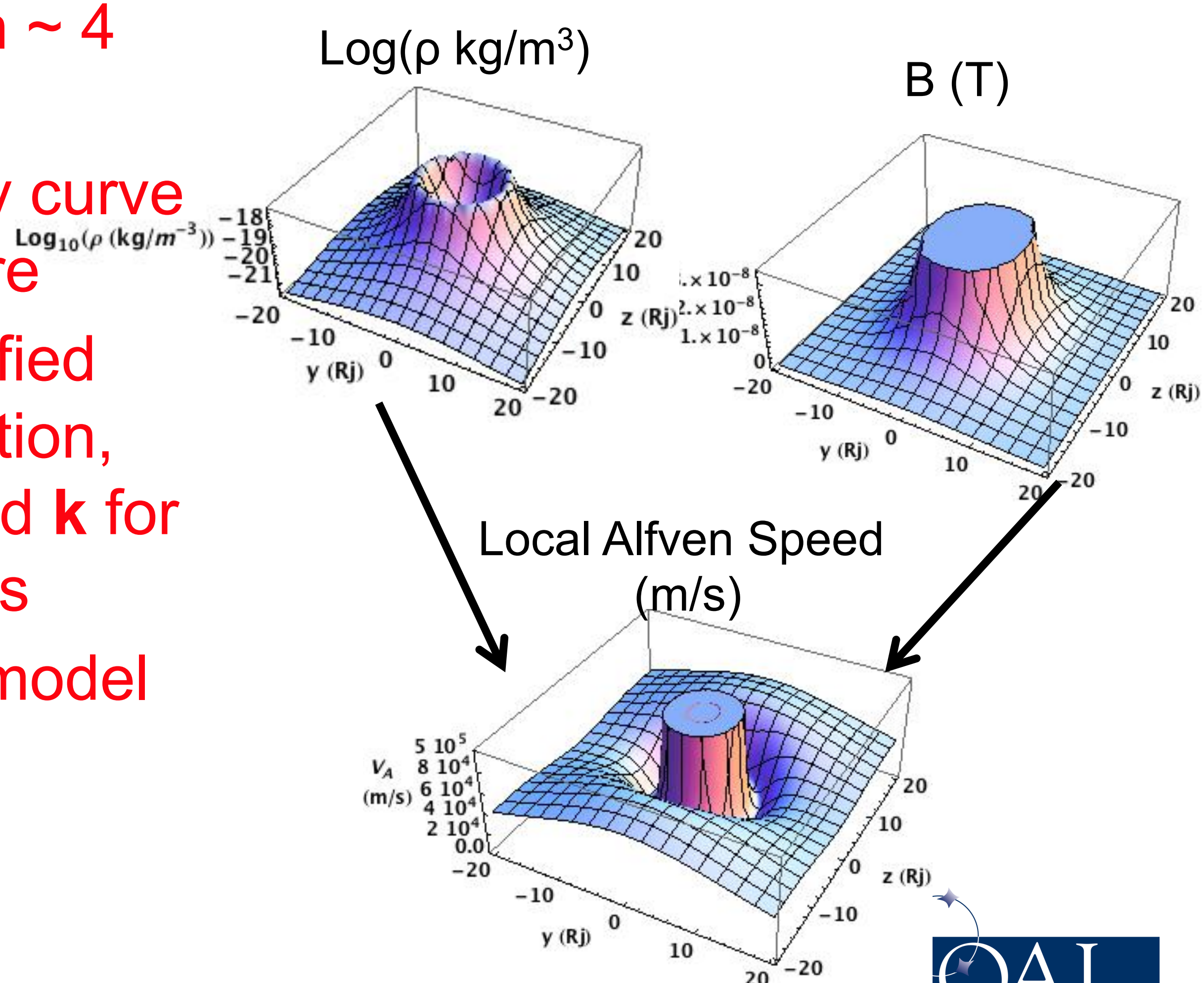




- Standardized simplified model for dipole fields allows calculation structure to be applied to multiple environments
  - Jovian and Terrestrial environments described to date

Jovian Magnetosphere

- Dipole strength ~ 4 nT Rj^3
- Plasma density curve fit from literature
- Using a simplified dispersion relation, calculate ω, and **k** for initial conditions
- Use full fields model for ray tracing



Antenna Modeling

- Antennas determine the dominant axial and perpendicular wavelengths launched
  - Antenna design determines types of fields
    - E, B - Axial, radial, azimuthal
  - Antenna dimensions determine dominant wavelengths
- The desired wavelengths are determined from local B and density values

Leveraging Resources through Collaboration

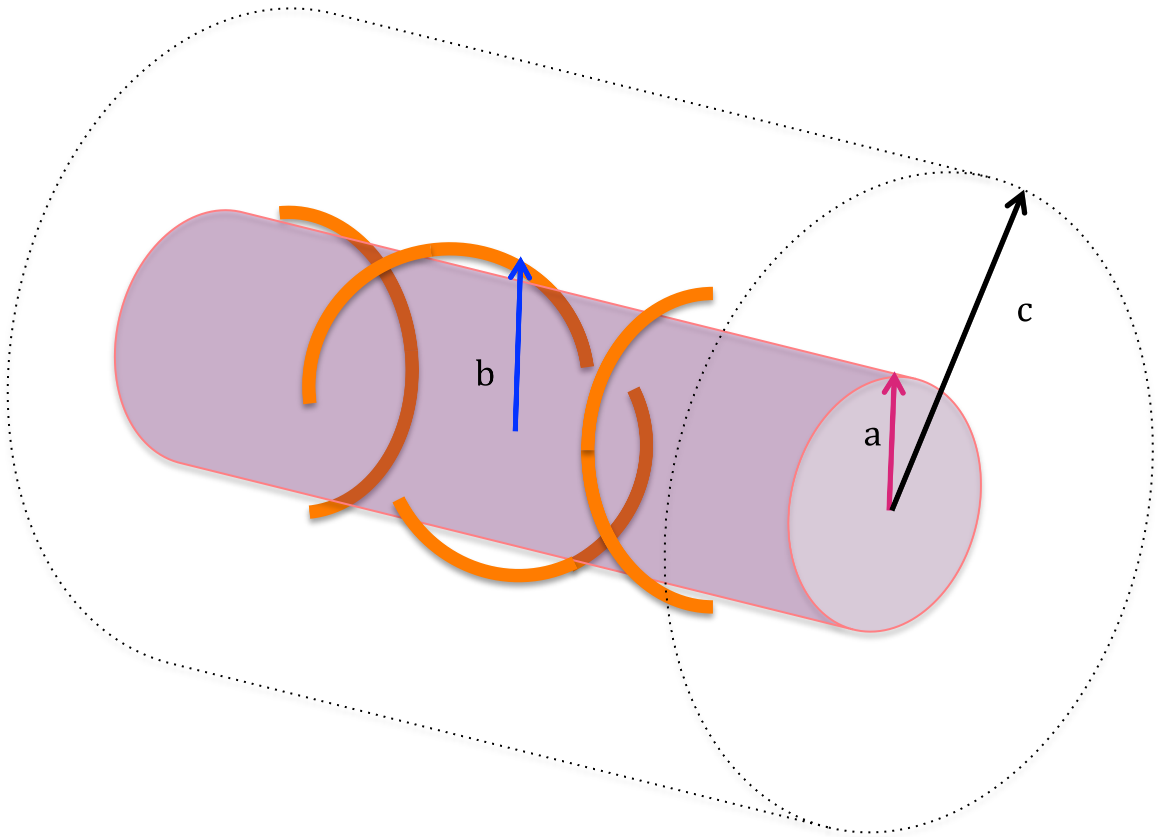
ANTENA Code

- Warm plasma cylindrical wave code
- Originally designed for fusion wave heating applications
  - Radial profiles of n_e, T_e (not self consistent)
  - Axially uniform B_0, n_e
  - Uses real antenna designs/wavelength spectra
  - Calculates radiated power, antenna/plasma coupling
- Can apply ANTENA to the calculated local plasma parameters to determine best antenna size, design for the wave propulsion application

Leveraging Resources through Collaboration

First Antenna Design Considered

- Phased semicircles in parallel
- Potential for changing k_z with phasing of current in the loops
- Considered $\pm \pi, \pi/2, \pi/4$ phasing of loops



Leveraging Resources through Collaboration

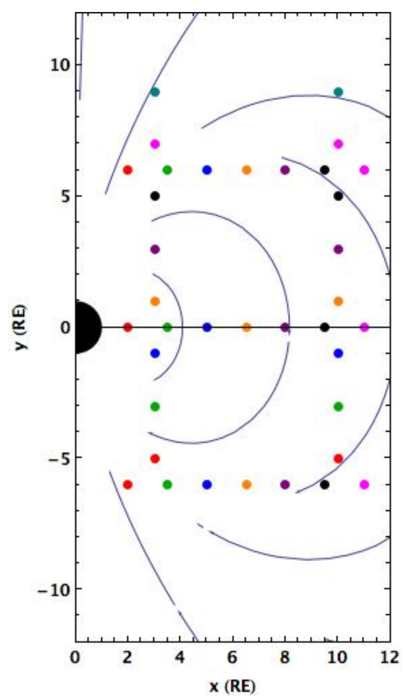
RESULTS

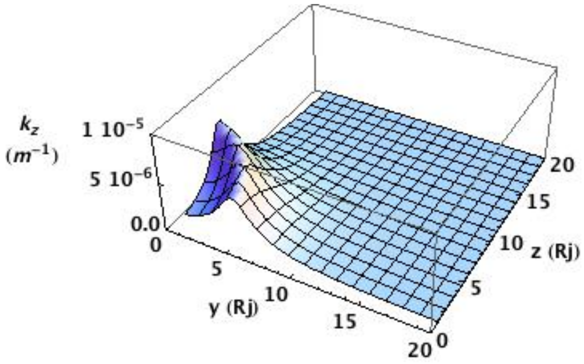
Ray Tracing Analysis

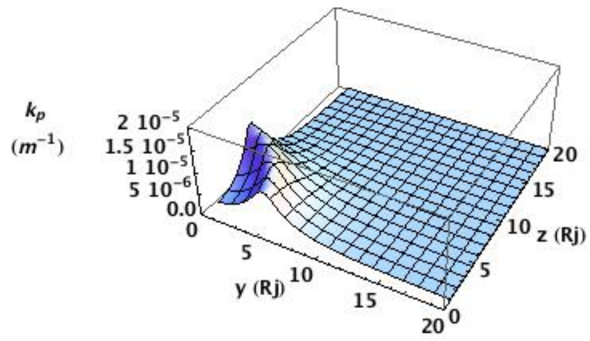
- Ray tracing analysis generated from first principles in Mathematica
- Initial conditions generated for multiple Alfven modes throughout terrestrial and Jovian magnetosphere
  – Fast modes also depend on $k_{\perp}$ - assumed to be $\approx k_z$ for initial calculations
- Wave propagation was been examined throughout the magnetospheres
  – Parallel and perpendicular waves observed
  – Currently examining results for resonance absorption and reflections

Ray tracing initial conditions

- Spatial locations span a range of conditions
  - ($2\ R_j < r < 25\ R_j$)
- Corresponding wavelengths (k_z, $k_\perp$) calculated as function of position for each of the 3 modes
- Full wave equation allows for mode conversion

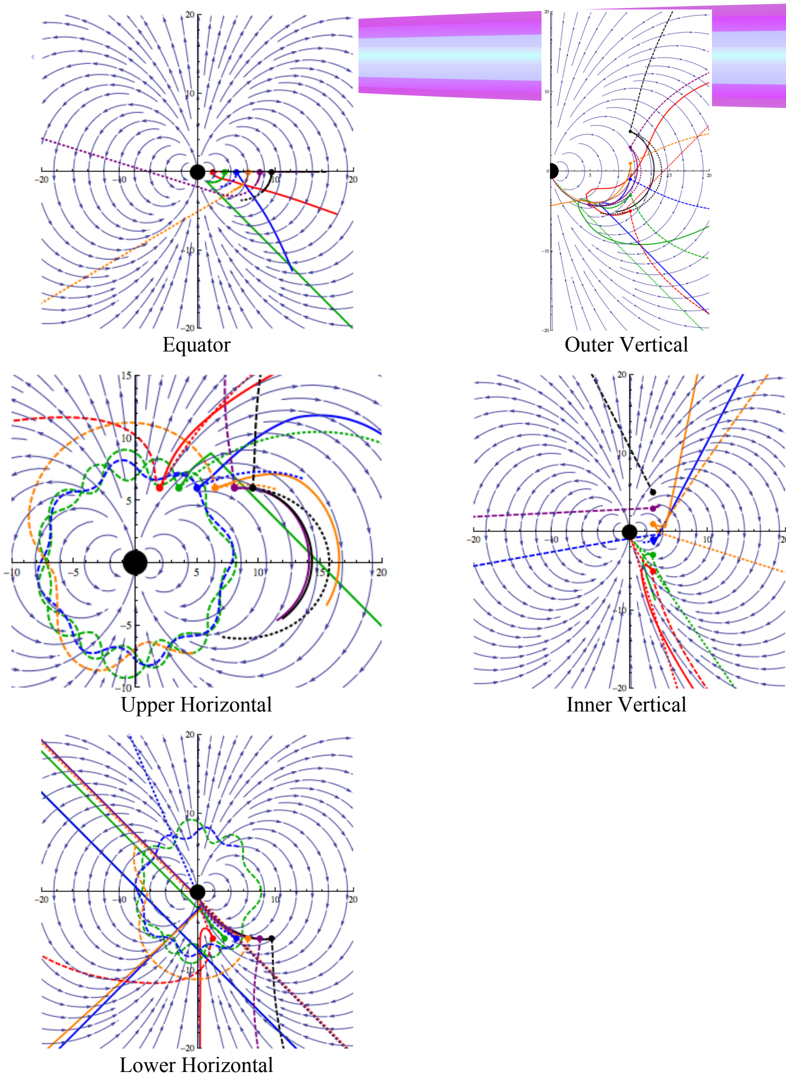




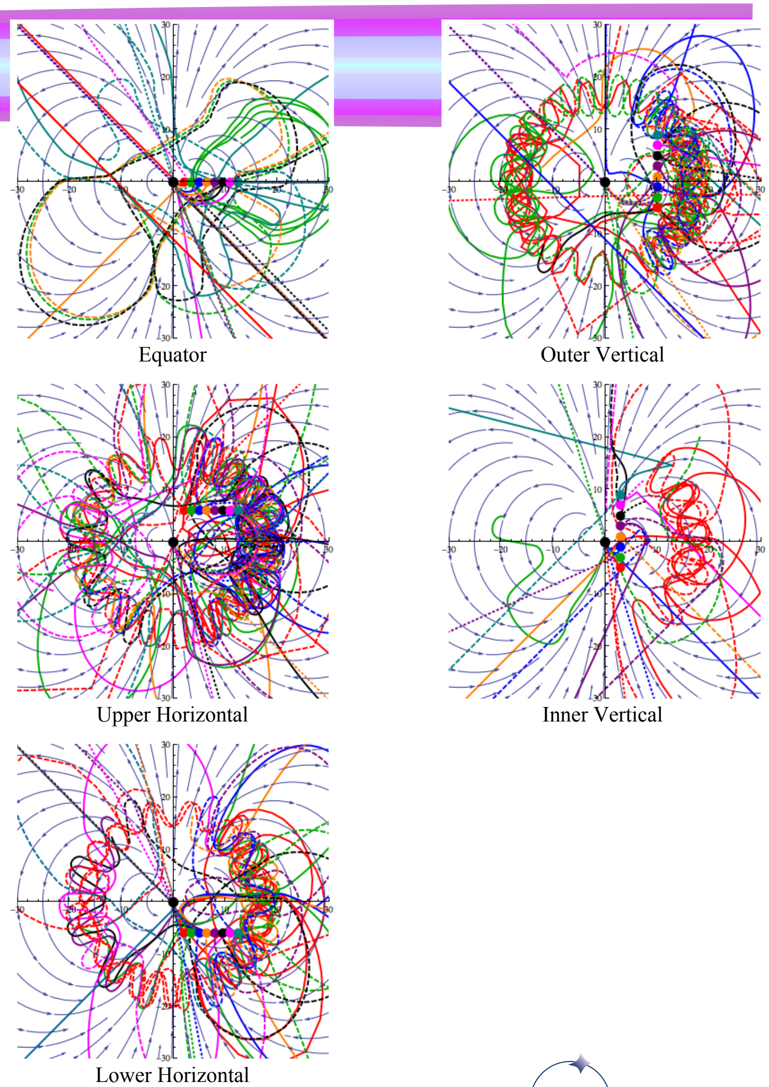


Leveraging Resources through Collaboration

Ray Tracing in Earth and Jupiter Magnetospheres



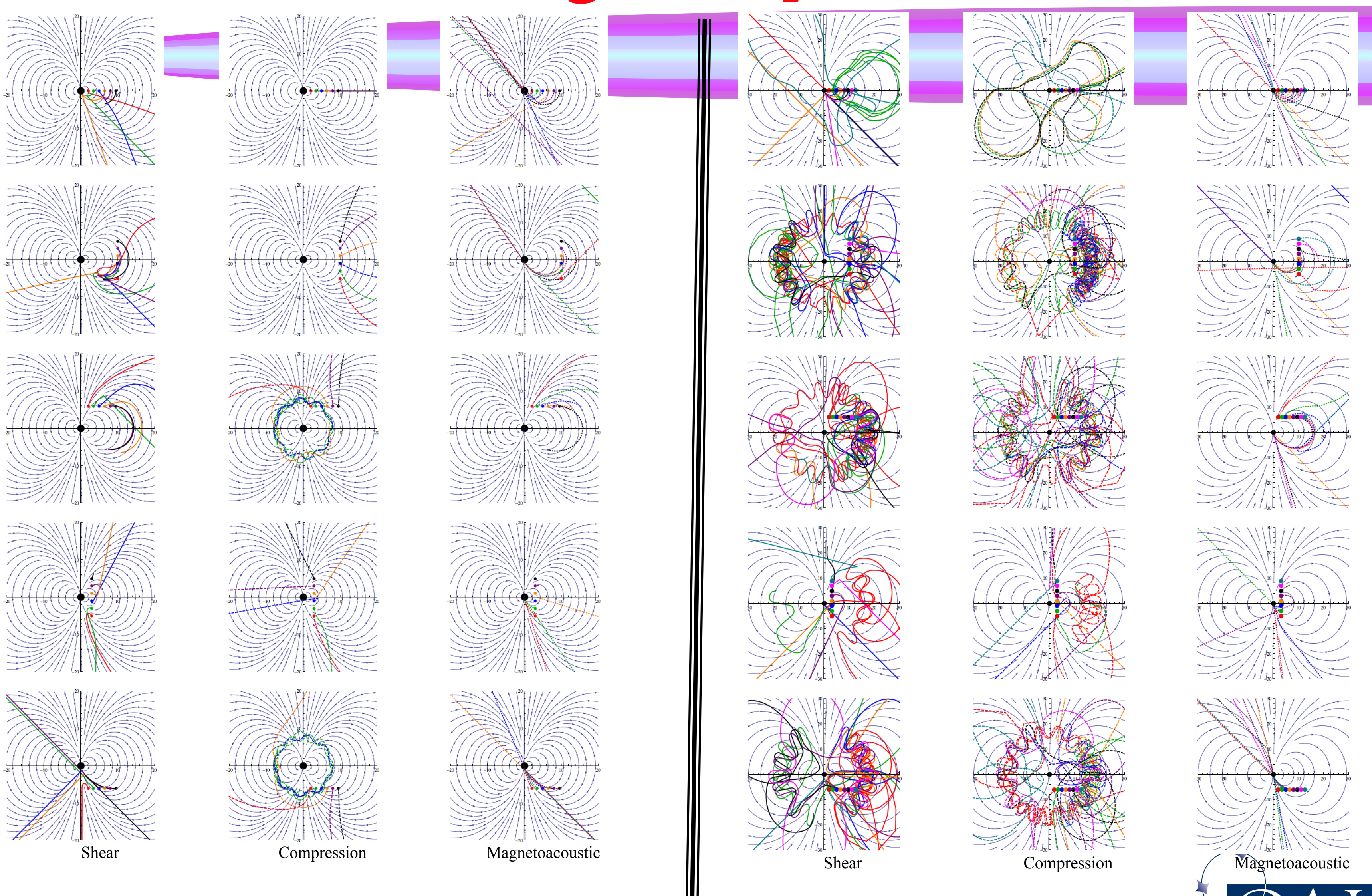
Jupiter



Earth

OAI
Leveraging Resources through Collaboration

Ray Tracing in Earth and Jupiter Magnetospheres



Jupiter

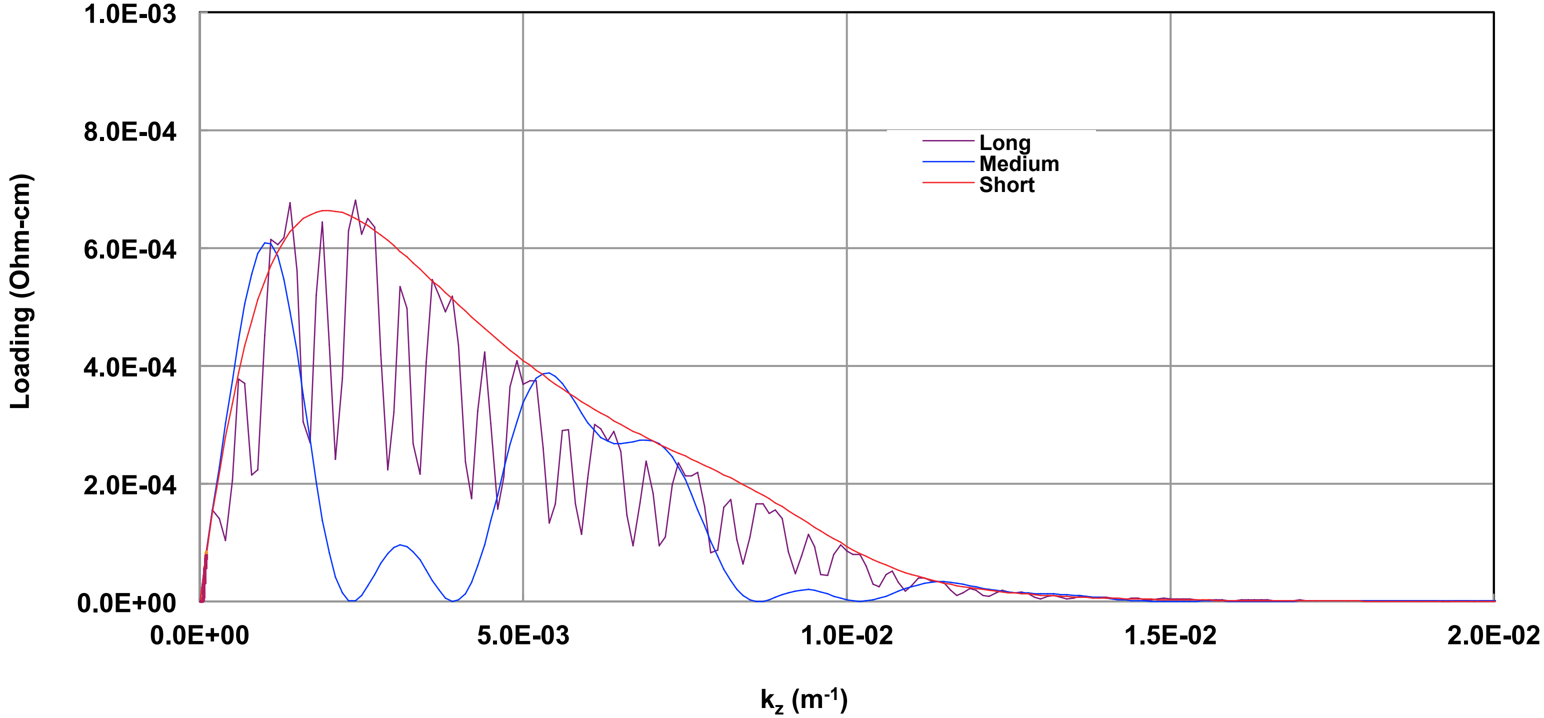
Earth

Leveraging Resources through Collaboration

Antenna System

- Initial conditions indicate large antenna dimensions, ~ 10 – 100’s km
- Some representative antenna in that size range have been modeled in the ANTENA code, using Jupiter magnetospheric B and density values
- Currently examining the effects of antenna size on coupling

Antenna Length studies

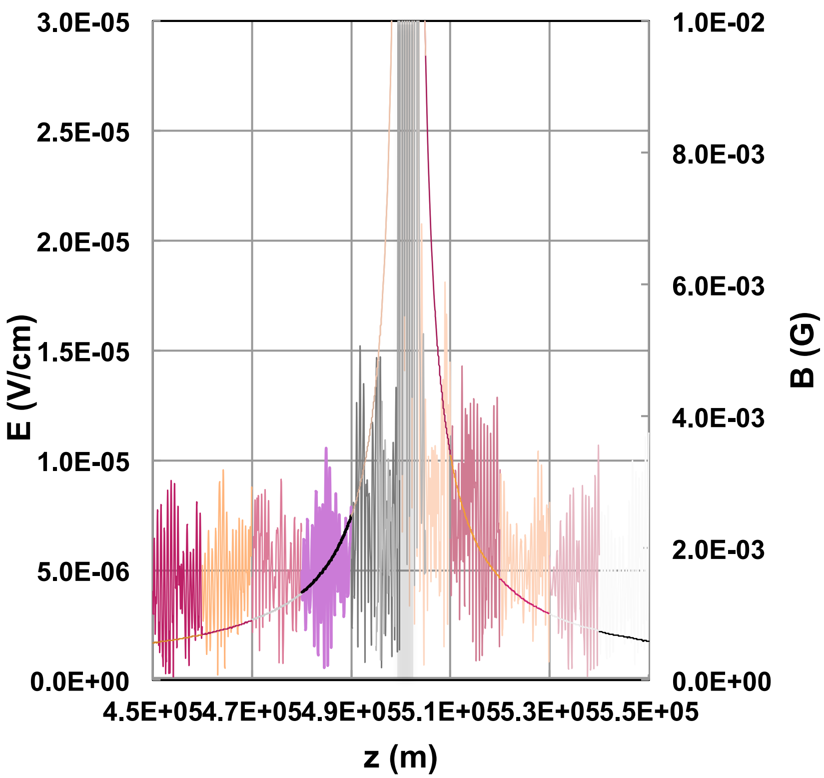


- Assumes
  - Fixed diameter: 500 m
  - Vary length from 500 – 1000 km, examine antenna loading, power deposition with k_z

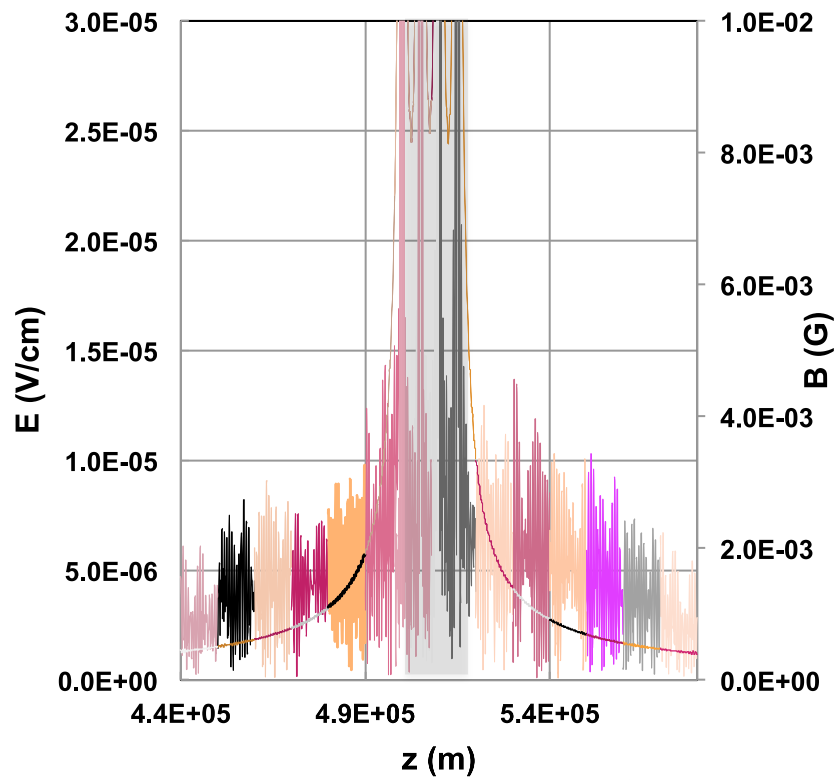
Leveraging Resources through Collaboration

Wave Fields from 2 Antenna Designs

Short Antenna



Long Antenna



OAI
Leveraging Resources through Collaboration

Force Estimation for Initial Antenna Designs

	Forces (N)			
Antenna	Left	Right	Net (➔ positive)	Thrust Density (N/m^2)
Short	703	480	-223	1.1×10^{-3}
Long	399	402	2.53	1.3×10^{-5}

- Net thrust is if both ends of antenna are left open to environment
- Short antenna provides greater net thrust

Summary of Results

- Ray tracing has shown feasibility of wave propagation
  - Different modes propagate in different directions depending on k_z, $k_\perp$
  - Some regions show potential for standing wave formation
- Antenna coupling shows the scale and efficiency of the process
  - 100's of km scale antenna necessary for magnetospheric environment
  - Narrow antenna diameter decreases coupling efficiency
- For antenna design considered:
  - 100's N thrust levels generated at currents
    - Corresponds to mN/m^2; lower than ion engine
  - Poor coupling leads to low efficiency

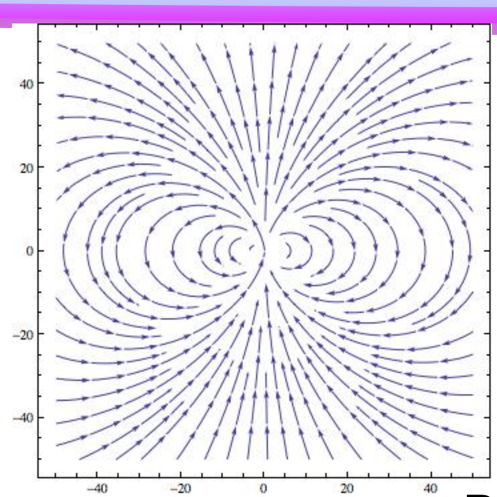
OAI
Leveraging Resources through Collaboration

Future Work

- Refine antenna designs
- Assess non-linear wave (“PIT”) option
- Apply analysis to helicon (Whistler) waves

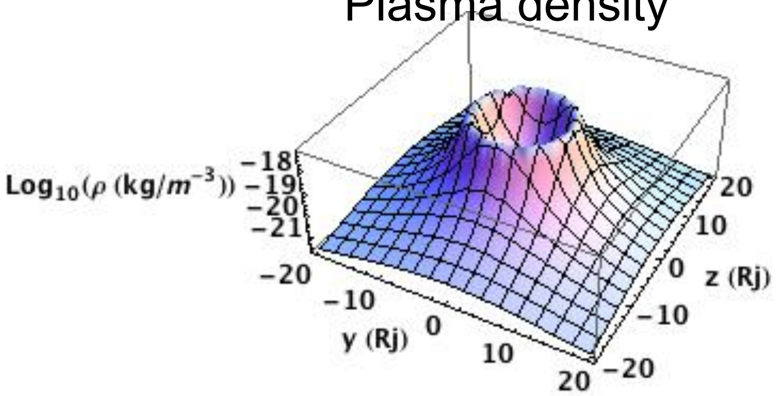
Establish Potential Environments

- First approximation Magnetospheres
  - Dipole magnetic field
  - Axisymmetric density
  - Uniform T_e
- Calculate simplified local k for ray tracing
- Assess ray propagation in spatially varying fields



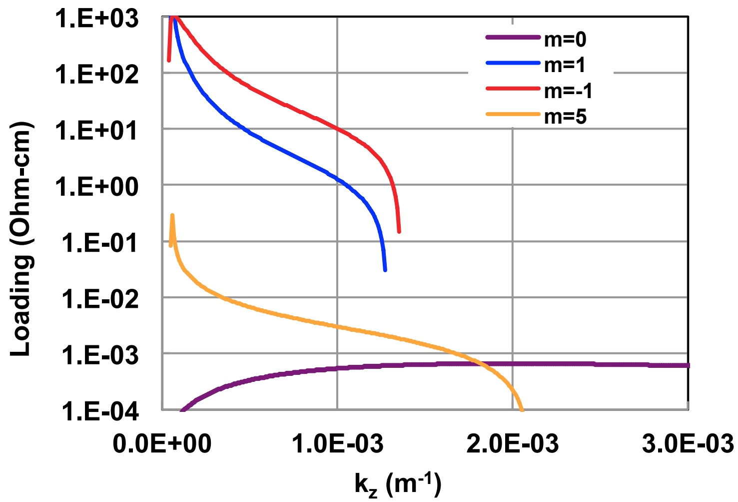
Magnetic Field

Plasma density



Leveraging Resources through Collaboration

Antenna Design Trades



- Coupling spectra for antennae of varying length and pitch

Leveraging Resources through Collaboration